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Effects of Whole-Tree and Stem-Only Clearcutting on Postharvest Hydrologic Losses, Nutrient Capital, and Regrowth

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ABSTRACT. Nutrient removal by sawlog or pulpwood harvest (SAW), and whole-tree harvesting (WTH) was determined for 11 forest stands located throughout the United States. Data from this study combined with previously published nutrient budgets indicated potential net losses of Ca and K at most sites without harvest, and net losses of N, P, K, and Ca with either SAW or WTH. Total stem biomass and nutrients were significantly correlated with total above-stump biomass, providing a means for estimating nutrient removals with WTH and SAW in commercial forests. Limited data from harvested stands indicated greater regrowth biomass with SAW than with WTH on some sites.

In the 11 harvested stands, hydrologic losses of N, K, and Ca generally increased immediately after harvest, but returned to levels comparable to control areas within 3 years. Because of the short duration of elevated nutrient losses, the hydrologic losses are considered minor relative to harvest removals. Ca and K are possible exceptions. The large difference in amounts of nutrients left on site in logging slash after SAW com-

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pared with WTH did not result in major differences in leaching or runoff at sites where comparisons were made. FOR. SCI. 34(2):412–428.

ADDITIONAL KEY WORDS. Whole-tree harvest, nutrients, biomass.

INCREASINGLY MECHANIZED AND INTENSIVE timber harvests have increased the potential of reduced future productivity of forest sites. In many forest stands, nutrient depletion by whole-tree harvest (WTH) is of concern (Weetman and Webber 1971, Boyle and Ek 1972, White 1974, Johnson 1983), but in other stands, WTH has little or no effect on total ecosystem nutrients (Miller et al. 1980, Hornbeck and Kropelin 1982). Evidence of reduced growth after repeated forest rotations is limited to a few studies (Rennie 1955, Stone and Will 1965, Keeves 1966, Smith et al. 1986). The potential for yield reductions in successive crops is greater with short rotations and intensive harvests because of the removal of disproportionately larger amounts of nutrients in the relatively nutrient-rich twigs, branches, and foliage (Boyle and Ek 1972, White 1984, Leaf 1979, Johnson et al. 1982).

In addition to direct losses of nutrients in timber crops, timber harvest often results in nutrient losses through leaching to groundwater, erosion, and surface runoff (Likens et al. 1977, 1978, Stone et al. 1978, Bormann and Likens 1979, Martin and Pierce 1979, McColl and Grigal 1979). Seldom has the magnitude of these losses in relation to total ecosystem nutrients been quantified for major commercial forests, and the relative effects of different intensities of harvest, such as whole-tree versus stem-only harvesting, are not known.

We examined the effects of whole-tree and stem-only clearcutting by comparative studies of uncut and clearcut stands at eight sites in the major timber harvesting areas of the United States. The objectives of this study were to (1) estimate probable changes in nutrient capital due to direct removal of nutrients with harvest, (2) estimate nutrient removal from harvested stands via hydrologic mechanisms, and (3) examine subsequent regrowth biomass following harvest. Data from the current study were combined with data from previously published studies to estimate comparative potential net nutrient balance with whole-tree and stem-only harvest.

METHODS

CURRENT STUDY SITES

Preharvest nutrient budgets were estimated for six hardwood and five conifer stands (Table 1) selected from the most heavily forested and harvested areas in the United States. The Washington site included four stand types: high- and low-fertility stands of both Douglas-fir (*Pseudotsuga menziesii*) and red alder (*Alnus rubra*). One stand type was used at each of the other sites. Several of the sites already had active research programs, and all research institutions were involved in other forest research related to nutrients and forest growth.

Preharvest biomass was estimated from inventories and regression equations that were derived from trees sampled for this study or from previous work on the site (Harris et al. 1973, Tritton et al. 1982, Van Lear et al. 1984). Merchantable sawlog or pulpwood stem biomass was determined from species, size, and form classes at the Oak Ridge, Coweeta, and Mt. Success sites and from species and diameter limits at the other sites (Table 1). Merchantability was determined from the traditional use of species in different regions of the United States.

Methods used in nutrient analyses of vegetation, litter, soil, leachate, runoff, and rainfall were reported in previous publications [Oak Ridge (Johnson et al. 1982); Washington (Bigger and Cole 1983); Mt. Success, Cockaponset, Chesuncook (Hornbeck and Kropelin 1982, Smith et al. 1986, Hornbeck et al. 1987); Florida (Conde et al. 1979, Morris 1981, Taras et al. 1971); Clemson (Van Lear et al. 1983); Coweeta (McSwain and Beale 1980, Boring et al. 1981, Swank 1984)]. Dissolved nutrient losses in subsurface water and stream runoff were compared between unharvested stands and stands that were either clearcut with only merchantable stems removed in conventional sawlog or pulpwood harvest (SAW), or clearcut with above-stump WTH. Nutrients removed from the site during SAW or WTH were calculated from estimated stem and branch biomass and nutrient contents. Atmospheric nutrient input was calculated from wet deposition or bulk precipitation collected at all sites. Asymbiotic N-fixation was estimated by the acetylene reduction method (Hardy et al. 1968) before and after harvest at the Clemson and Coweeta sites and from previous work at the Florida site. Dissolved nutrient losses via subsurface leaching and runoff were estimated from leachate collected in porous-cup tension lysimeters installed at or below maximum feeder root depth and from weirs on sites with surface runoff or perennial streams. Runoff used to calculate nutrient losses at the Mt. Success, Chesuncook, and Cockaponset sites was estimated by the hydrologic model "Brook" (Federer and Lash 1978).

Natural regeneration followed harvest at all sites except the Washington Douglas-fir sites where Douglas-fir seedlings were planted and the Florida site, where *Eucalyptus viminalis* seedlings were planted. Total biomass was measured for 1 to 5 years after harvest at three of the five sites (Oak Ridge, Clemson, and Coweeta) that had both WTH and SAW treatments and at one site (Cockaponset) with only WTH.

Previously Published Data from Other Sites

To enhance our ability to predict the effects of SAW and WTH, we compared our data with previously published data from a wider range of sites that encompassed a greater diversity of species and site characteristics. Our objectives were twofold: (1) to determine how representative our sites were of forests in general and, (2) to determine if the combined sources of data could be used to predict nutrient removals from biomass and net hydrologic losses of nutrients from both harvested and unharvested stands. Only data from stands between 25 and 100 years of age were used (Marion 1979, Cole and Rapp 1981, Kimmins et al. 1986). Conifers and hardwoods were evaluated separately.

RESULTS

Biomass and Nutrient Partitioning to Stems and Residues—Current Study

Total biomass in harvested hardwood stands averaged approximately 25% less [147 (±25 SD) Mg/ha] than total biomass in harvested coniferous stands [191 (±84 SD) Mg/ha] (Table 2). Merchantable stem biomass ranged from 24 to 93% of total above-stump biomass, averaging considerably less in hard-

TABLE 1. *Descriptions of sites, stands, and types of harvest.*

Site (Site name in parentheses)	Latitude/ longitude	Dominant species	Age (yr)
Oak Ridge National Environmental Research Park, Oak Ridge National Laboratory, TN (Oak Ridge)	36° N/84° W	*Quercus prinus, Quercus* sp., *Carya* sp., *Acer rubrum*	Mixed: 80
Charles Lathrop Pack Forest, University of Washington, WA (Washington)	47° N/122° W	Two *Alnus rubra* and two *Pseudotsuga menzieseii* stands	55
Great Northern Paper Company timberlands, Northeastern Forest Experiment Station and University of Maine, Chesuncook Lake, ME (Chesuncook)	46° N/69° W	*Picea rubens* and *Abies balsamea*	60
Cockaponset State Forest, Northeastern Forest Experiment Station, CT (Cockaponset)	41° N/72° W	*Quercus* sp., *Carya* sp., *Acer rubrum, Betula lenta*	Mixed: 80
James River Company timberlands, Northeastern Forest Experiment Station, Mt. Success, NH (Mt. Success)	44° N/71° W	*Acer saccharum, Betula alleghaniensis, Fagus grandifolia*	Mixed: 45
Nantahala National Forest, Coweeta Hydrologic Laboratory, Otto, NC (Coweeta)	35° N/84° W	*Quercus* sp., *Acer rubrum, Liriodendron tulipifera*	70
Clemson Experimental Forest, Clemson University, SC (Clemson)	34° N/83° W	*Pinus taeda*	41
Bradford Forest, University of Florida, FL (Florida)	30° N/82° W	*Pinus elliottii* replanted to *Eucalyptus viminalis*	30

[a] SAW = sawlog removal with clear-cut, WTH = above-stump whole-tree harvest.

wood stands [83 ($\pm$33 SD) Mg/ha or 57% of total biomass] than in coniferous stands [150 ($\pm$78 SD) Mg/ha or 79% of total biomass]. In three of the hardwood stands (Oak Ridge, Coweeta, and Mt. Success), less than 50% of the total biomass was in merchantable stems, while stems in the two alder stands contained 93% of the above-stump biomass.

The average proportion of above-stump nutrients in conifer stems (51, 49, 59, and 58% of total above-stump N, P, K, and Ca, respectively) was similar to that in hardwood stems (51, 44, 54, and 55%) (Table 2). The proportions of nutrients in stems of alder stands, however, were much higher than proportions in other hardwoods, ranging from 82% of total P to 91% of total Ca. Stems of hardwoods other than alder averaged 36, 23, 38, and 46% of above-stump N, P, K, and Ca, respectively.

TABLE 1. Continued.

Study site size (ha)	Soils	Landscape position	Type of harvest
0.36 (control) 0.81 (SAW)[a] and 0.79 (WTH)[a]	Ultisols	Upper slope, contiguous northwest facing, 5 to 45% slope	WTH and SAW to 25 cm dbh
5	Inceptisols	Level bottomland and midslope	WTH and SAW to 10 cm top diameter
72 (control), 47 (WTH)	Histosols, Inceptisols, Spodosols	Watershed	WTH
6	Inceptisols	Watersheds	WTH
10 (control) 6 (WTH)	Haplorthods	Upper slope watersheds 15 to 20% slopes	WTH
12.5 (control) 0.67 (WTH) 59 (SAW)	Dystrochrepts Hapludults	Upper slope watersheds	WTH and SAW to 20 cm top diameter
2.2 (control) 1.24 (WTH) 1.1 (SAW)	Ultisols	Upper and midslope watersheds	WTH and SAW to 5 cm top diameter
140 (control) 4.2 (WTH)	Spodosols	Nearly level, artificially contained watersheds	WTH

Biomass and Nutrient Partitioning to Stems and Residues—Previously Published Data

Accumulations of N, P, and K in the stems of trees and in entire trees were highly variable in previously published data. Variability was as great within individual species or genera as between conifers and hardwoods, but positive slopes of regressions indicated that nutrient accumulation was generally related to total above stump biomass (Table 3). In addition, the relationship of stem to total biomass was remarkably constant for both hardwoods and conifers (Figure 1). Although regressions for stem weights of hardwoods and conifers were significantly different, the magnitude of the difference was small. Stem weights were approximately 70% of total biomass across a broad range of values and species (Figure 1). In these data, total stem biomass could not be distinguished from merchantable stem biomass.

TABLE 2. Nutrient and biomass removals by SAW and WTH, arranged in descending order of WTH biomass. WTH removals were approximately equal to total stand biomass.

Site	SAW[a] biomass (Mg/ha)	SAW (kg/ha)				WTH[b] biomass (Mg/ha)	WTH (kg/ha)			
		N	P	K	Ca		N	P	K	Ca
Conifers										
Washington										
High[c] Douglas-fir	281	478	56	225	23	318	728	96	326	411
Chesuncook	155	141	19	121	272	232	410	59	245	537
Washington										
Low[c] Douglas-fir	134	161	27	81	NA[d]	165	325	56	140	NA
Clemson	85	63	6	35	71	110	123	10	56	111
Florida	58	59	5	20	80	106	110	10	35	138
Hardwoods										
Coweeta	43	58	7	48	130	178	277	41	216	544
Oak Ridge	64	110	7	36	410	175	323	23	128	1090
Cockaponset	121	162	5	108	442	158	273	19	162	530
Washington										
High alder	137	287	41	151	388	147	347	47	174	426
Low alder	111	311	22	122	NA	120	378	27	143	NA
Mt. Success	48	67	4	43	129	111	242	19	128	344

[a] SAW = sawlog removal with clear-cut.
[b] WTH = above-stump whole-tree harvest.
[c] High = high-fertility site, low = low-fertility site.
[d] NA = not available.

Total above-stump nutrient accumulation was more closely correlated with total stand biomass of hardwoods than with that of conifers. Of the four macronutrients considered, Ca accumulation showed the least correlation with total biomass (Table 3).

Combined biomass and nutrient estimates indicated that while approximately 80% of the conifer biomass was in stem tissue, only approximately 60% of the total nutrients was in the stem. Although proportionally less total

TABLE 3. Results of regression analyses comparing stem biomass (Mg/ha) and nutrient storage (kg/ha) to total above-stump biomass. Regressions are of the form Y = B*0* + B*1**X, *where* Y = *stem biomass (Mg/ha) or total above-stump storage of nitrogen, phorphorus, potassium, or calcium (kg/ha);* B*0* = *intercept;* B*1* = *slope; and* X = *total above-stump biomass (Mg/ha).*

Component	Type	n[a]	B0	B1	R2		C[b] vs H
Biomass	Conifers	34	−6.5	0.83	0.96	***[c]	**
	Hardwoods	15	16.0	0.66	0.93	***	
Nitrogen	Conifers	77	77.4	1.43	0.49	***	***
	Hardwoods	25	−25.5	2.97	0.79	***	
Phosphorus	Conifers	70	12.4	1.43	0.31	***	
	Hardwood	23	7.4	0.20	0.67	***	
Potassium	Conifers	73	30.4	0.9	0.64	***	***
	Hardwoods	25	30.5	1.31	0.74	***	
Calcium	Conifers	58	104.5	1.05	0.14	***	***
	Hardwoods	25	222.9	2.39	0.31	**	

[a] Number of samples. Data used in the analyses were from Marion 1979, Cole and Rapp 1970, and Kimmins et al. 1986.
[b] Significant differences in conifer (C) hardwood and (H) regressions.
[c] ** = $P < 0.01$, *** = $P < 0.001$.

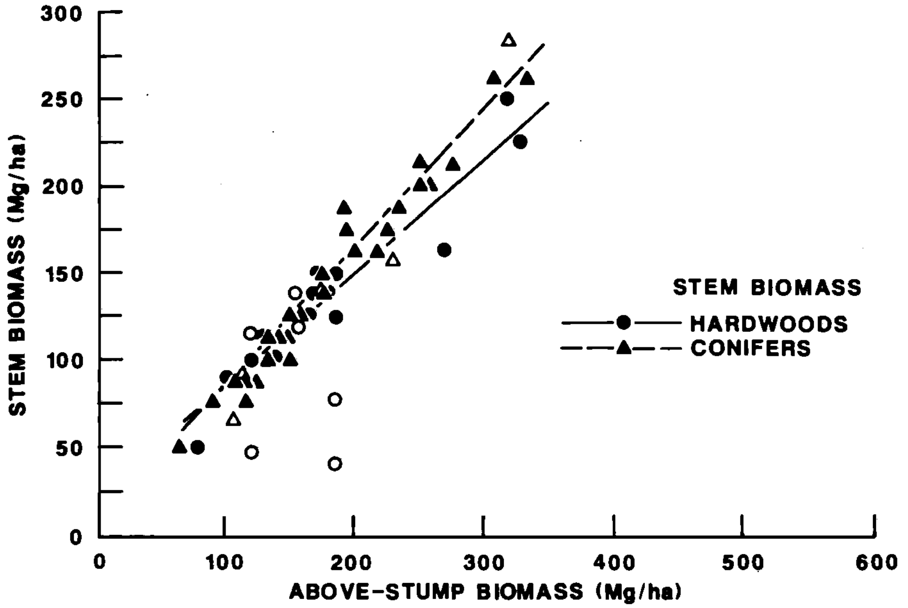

FIGURE 1. Relationship of stem biomass to total above-stump biomass. Current study data (open symbols) are merchantable stem weights. Previously published data (closed symbols) are from unharvested stands and do not differentiate total stem from merchantable stem. Regression relationships are indicated by solid (hardwoods) and dashed (conifers) lines.

biomass was in stem tissue in hardwoods (approximately 60%) than in conifers, the proportion of total stand nutrients in stem tissue was similar (approximately 60%), an indication of higher nutrient concentrations in the hardwood stems than in the conifer stems.

COMPARISON OF CURRENT AND PREVIOUSLY PUBLISHED BIOMASS AND NUTRIENT BUDGET DATA

Biomass at our sites was near the midrange of values from previously published data (Figure 1). Estimated merchantable stem biomass was similar to estimated total stem biomass from previously published data with the exception of three of the eastern hardwood sites: Oak Ridge, Coweeta, and Mt. Success. At these sites, estimates of merchantable stem biomass were considerably less than those of total stem biomass because of nonmerchantable species, limits of sawlog utilization, stems less than the diameter limit of the cut and defective trees (unsuitable form, hollow, or rotten).

Merchantable stem N and P data from Oak Ridge, Mt. Success, and Coweeta were unlike previously published hardwood stem data because of these differences in merchantable and total stem biomass. Total N and P values for our sites fell mostly within the range of values reported in the literature, however, with the possible exceptions of (1) Coweeta, which was low in N compared to other hardwood stands, (2) Cockaponset, which was low in P compared to other hardwood stands, and (3) the high-fertility Douglas-fir site, which was high in N compared to other conifer stands. Stem N in the high-fertility Douglas-fir data was also higher than that in the previously published conifer stem data.

Although Ca data from harvested sites were variable, they fell within the range of values previously reported from other studies, except for those at Oak Ridge. High values from the Oak Ridge site were partly due to high concentrations of Ca in hickory (*Carya* spp).

Only two of the sites had sediment losses, Florida and Clemson. Oak Ridge and Washington did not have sediment losses because there were no streams draining these sites and surface erosion did not occur. Mt. Success, Cockaponset, Chesumcook, and Coweeta did have streams draining their sites, but buffer strips were left along streams and logging was conducted in such a way to minimize surface erosion. Sediment losses from these sites were minimal and were not measured. Although similar care was taken at Clemson, sediment losses did increase after harvest, which appeared to be due to increased channel scouring as a result of higher flow following cutting (Van Lear et al. 1986). Extensive site preparation at Florida resulted in some erosion at that site. Although sediment losses contributed to nutrient loss at some sites, we only considered dissolved nutrient losses in the following discussion.

Nutrient concentrations in lysimeter collections and stream water tended to increase after harvest, but the magnitude, duration, and elements involved varied from site to site (Table 4). Nitrate and K^+ most frequently changed in both runoff and leachate after SAW and WTH. The alder stands were the only sites where NO_3^-, PO_4^-, and K^+ losses in leachate decreased, but several sites showed a decrease in NH_4^+ losses. Water quality standards

TABLE 4. Changes in nutrient concentrations and sediment in stream runoff and leaching after harvest.

Site	Runoff	Soil solution
Pack Forest		
Douglas-fir, high fertility	NA[a]	Slight increase in Ca^+ first year; decrease in NH_4^+ first year
Douglas-fir, low fertility	NA	Decrease in K^+ first year
Red alder, high fertility	NA	Decrease in NO_3^-, K^+, and Ca^+ first two years
Red alder, low fertility	NA	Decrease in NO_3^-, K^+, and Ca^+ first two years
Chesuncook	Increase in NO_3^-, Ca^+, K^+; decrease in SO_4^{-2}	Increase in Ca^+ and NO_3^- first 3 years
Cockaponset	Increase in NO_3^-, Ca^+, and K^+	Increase in NO_3^-
Mt. Success	Increase in NO_3^-, Ca^+, and K^+	Increase in NO_3^-, Ca^+, and K^+ the first 2 years
Coweeta	NA	Increase in total N, PO_4^-, K^+, Ca^+ for from 6 months to 3 years; decrease in Ca^+ after first year
Oak Ridge	NA	Slight increase in NO_3^-
Clemson	Increase in sediment and NO_3^-; decrease in NH_4^+	Increase in NO_3^-; decrease in NH_4^+
Bradford	Increase in sediment, Ca^+, and K^+; decrease in total N	

[a] NA = not applicable.

for NO_3-N (10 ppm NO_3-N) were exceeded only in groundwater at Mt. Success the first year after WTH (maximum 21.4 mg/L, average 6.9 mg/L) and in the uncut alder control site.

Changes in total amounts (kg/ha) of dissolved nutrients "lost" by leaching below the rooting zone or by runoff were also highly variable. Some sites lost less nutrients after harvest than control sites, but other sites lost nutrients in greater amounts immediately after harvest when compared with controls (Figure 2). Nitrogen losses ranged from 10.7 kg/ha more than losses from the control site the first year after WTH at Cockaponset to a net decrease in N losses at the high-fertility alder site after both SAW and WTH. Phosphorus losses were very low (less than 0.06 kg $\cdot$ ha^{-1} $\cdot$ yr^{-1}) at all sites after both SAW and WTH except after WTH at the high fertility Douglas-fir site. Both K^+ and Ca^+ losses initially increased after WTH and SAW at most sites but approached control levels in succeeding years. A paired t-test

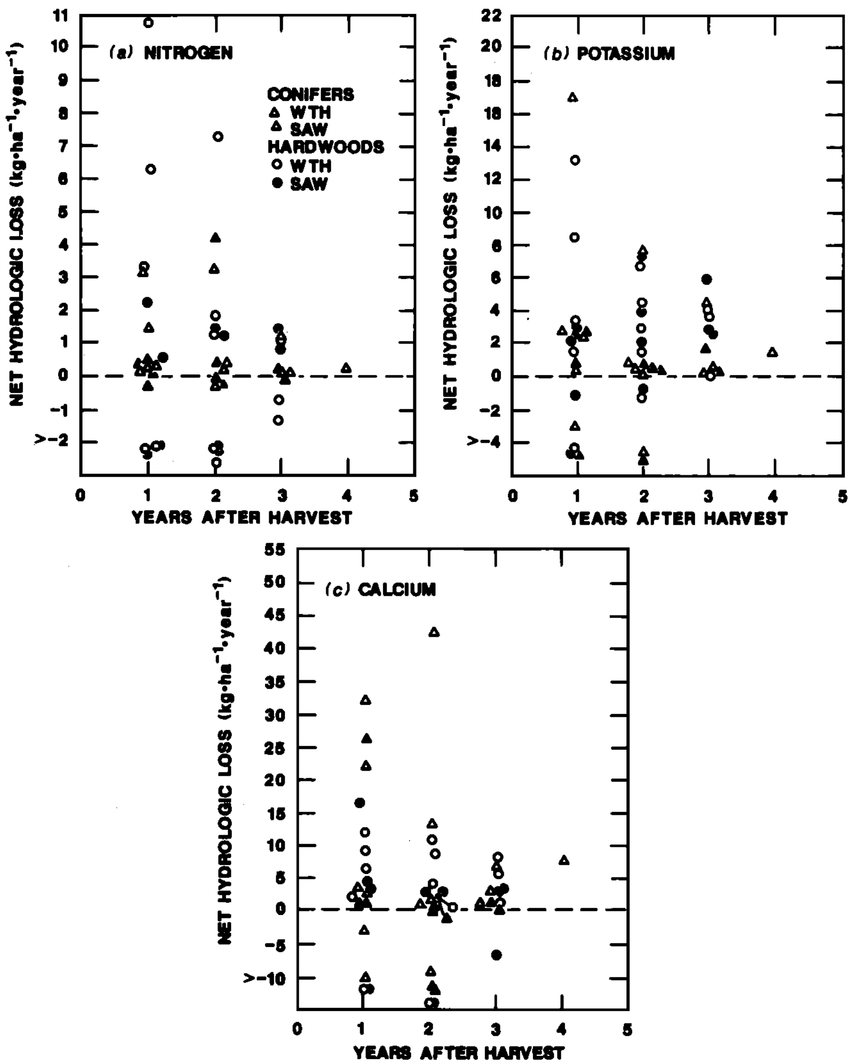

FIGURE 2. Net changes in hydrologic losses of nutrients after harvest. Values are differences between harvested and control sites.

of annual leaching losses across all sites showed losses of P were significantly larger ($P < 0.10$) after WTH than after SAW. Losses of N were greater after SAW than after WTH ($P < 0.09$), but only during the second year after harvest.

Although hydrologic nutrient losses might be expected to be related to nutrients left on-site after harvest, this was not evident. Hydrologic nutrient losses were compared with total nutrient capital, as well as with separate ecosystem components (soil, extractable soil, litter, unharvested woody residues) in harvested and unharvested stands. There were no clear relationships.

Comparison of Nutrient Removals in Harvest and Changes in Nutrient Losses in Leaching and Runoff

Nutrient removals by SAW ranged from 58 to 478 kg/ha N, 4 to 56 kg/ha P, 20 to 225 kg/ha K, and 71 to 442 kg/ha Ca (Table 2). Removals by WTH were 110 to 728 kg/ha N, 10 to 96 kg/ha P, 35 to 326 kg/ha K, and 111 to 1090 kg/ha Ca. To compare direct removal of nutrients in harvested wood (Table 2) with hydrologic nutrient losses across stands of different ages, harvest removals (Table 5) were expressed in terms of annual nutrient accumulation, calculated by dividing harvest removals by stand age ($kg \cdot ha^{-1} \cdot yr^{-1}$). Harvest removals by SAW ranged from 0.8 to 8.7 $kg \cdot ha^{-1} \cdot yr^{-1}$ N, 0.08 to 1.02 $kg \cdot ha^{-1} \cdot yr^{-1}$ P, 0.5 to 4.1 $kg \cdot ha^{-1} \cdot yr^{-1}$K, and 1.7 to 7.1 $kg \cdot ha^{-1} \cdot yr^{-1}$ Ca (Table 5). Removals by WTH ranged from 2.7 to 13.2 $kg \cdot ha^{-1} \cdot yr^{-1}$ N, 0.24 to 1.75 $kg \cdot ha^{-1} \cdot yr^{-1}$ P, 0.5 to 4.1 $kg \cdot ha^{-1} \cdot yr^{-1}$ K, and 2.7 to 13.6 $kg \cdot ha^{-1} \cdot yr^{-1}$ Ca.

The average annual net change in hydrologic loss of nutrients over the time of the study (total nutrients lost divided by years since harvest) was used to provide a crude estimate of maximum nutrient losses due to harvest. In most cases, removals of nutrients in wood with WTH exceeded hydrologic nutrient losses (Table 5). Accelerated hydrologic losses of K often exceeded harvest removals, but at several sites, losses returned to preharvest levels by the end of the sampling period (Figure 2 and Table 5). Because of the high initial hydrologic losses of K and the variability among sites, it was not possible to determine the relative impact of harvest removals versus additional hydrologic losses of K. Hydrologic losses of Ca also exceeded harvest removals at serveral WTH sites and decreases followed a similar pattern to that for K at most sites. With SAW, hydrologic losses of all macronutrients were often comparable to or larger than harvest removals of nutrients but, as was the case for WTH, losses generally decreased with time after harvest.

Net Nutrient Fluxes: Deposition, Leaching, and Harvest Removals

Figure 3 shows a comparison of annual balances of inputs in precipitation minus annual hydrologic losses from uncut stands, with projected nutrient removals by SAW and WTH from our sites and from sites reported in previously published data. Annual net hydrologic changes did not include changes in hydrologic losses due to harvest because (1) increased hydrologic losses of nutrients were short-lived relative to the length of the rotation, and (2) data from the literature were from uncut sites. Nutrient removals in harvested wood were calculated as mean annual accumulation, which averaged changes in accumulation rate during the rotation. The diag-

TABLE 5. Comparison of harvest removals and stream or leaching losses of nutrients (kg · ha⁻¹ · yr⁻¹). Leaching or stream losses are net differences between cut and uncut watersheds.

	Nitrogen		Phorphorus		Potassium		Calcium		
Site	Harvest Removal	L/S[a]	Harvest Removal	L/S	Harvest Removal	L/S	Harvest Removal	L/S	Years[b]
ORNL									
SAW	1.4	<1.8	0.09	<0.02	0.5	<5.3	5.1	<3.2	2
WTH	4.0	<2.2	0.29	<0.05	1.6	<6.3	13.6	<3.7	2
Chesunc									
SAW	2.4		0.31		2.0		4.5		
WTH	6.8	1.5	0.98	NR[c]	4.1	7.7	9.0	12.6	4
Cockapon									
SAW	2.0		0.06		1.4		5.5		
WTH	3.4	6.3	0.24	NR	2.0	7.9	6.6	6.2	3
Mt. Success									
SAW[d]	1.5	2.1	0.08	LC[e]	1.0	2.9	2.9	LC	10
WTH	5.4	2.3	0.42	NR	2.8	1.9	7.6	9.9	3
Clemson									
SAW	1.5	0.3	0.15	0.01	0.9	1.7	1.7	0.4	3
WTH	3.0	0.2	0.24	0.11	1.4	0.2	2.7	2.7	3
Bradford									
SAW	1.4	LC	0.12	0.01	0.5	0.3	2.0	0.1	3
WTH	2.7	0.1	0.24	0	0.9	0.8	3.4	1.0	3
Coweeta									
SAW[d]	0.8	0.93	0.10	0.07	0.7	2.13	1.9	2.8	3
WTH	4.0		0.59		3.1		7.8		
Washington[f]									
DFH-SAW	8.7	2.2	1.02	LC	4.1	1.7	4.2	LC	2
DFH-WTH	13.2	0.1	1.75	0.33	5.3	1.9	7.5	38.0	2
DFL-SAW	2.9	<0.1	0.49	LC	1.5	LC		26.1	2
DFL-WTH	5.9	1.8	1.02	LC	2.6	LC		LC	2
AH-SAW	5.2	LC	0.75	LC	2.8	LC	7.1	LC	2
AH-WTH	6.3	LC	0.85	LC	3.2	LC	7.8	LC	2
AL-SAW	5.7	LC	0.40	0	2.2	LC		8.8	2
AL-WTH	6.9	LC	0.49	0	2.6	0.5		6.0	2

[a] Leaching and/or stream losses averaged for years samples (2 to 4 years).
[b] Number of sample years postharvest.
[c] NR = not reported: usually below detection limits.
[d] Hydrologic losses for SAW from earlier study on a similar site.
[e] LC = less than control.
[f] DFH = Douglas-fir, high fertility; DFL = Douglas-fir, low fertility; AH = alder, high fertility; AL = alder, low fertility.

onal line in Figure 3 defines the net nutrient input required to balance nutrient removals in harvest. Additions from mineral weathering or dry deposition were not included. Approximately 40% of the sites showed a net loss of N with SAW compared with 80% showing a net loss with WTH (Figure 3a). Nitrogen-fixation inputs were not known for all sites, but for those sites that did have N-fixation data (Clemson, Florida, and Coweeta), N was accumulating at a faster rate than mean annual accumulation for SAW or WTH. The Clemson loblolly pine site, which had received three low-intensity prescribed burns late in the rotation was an exception. If symbiotic N-fixation had been included, the Clemson site would probably have had a positive N balance even with burning. McKee (1982) showed that nitrogen

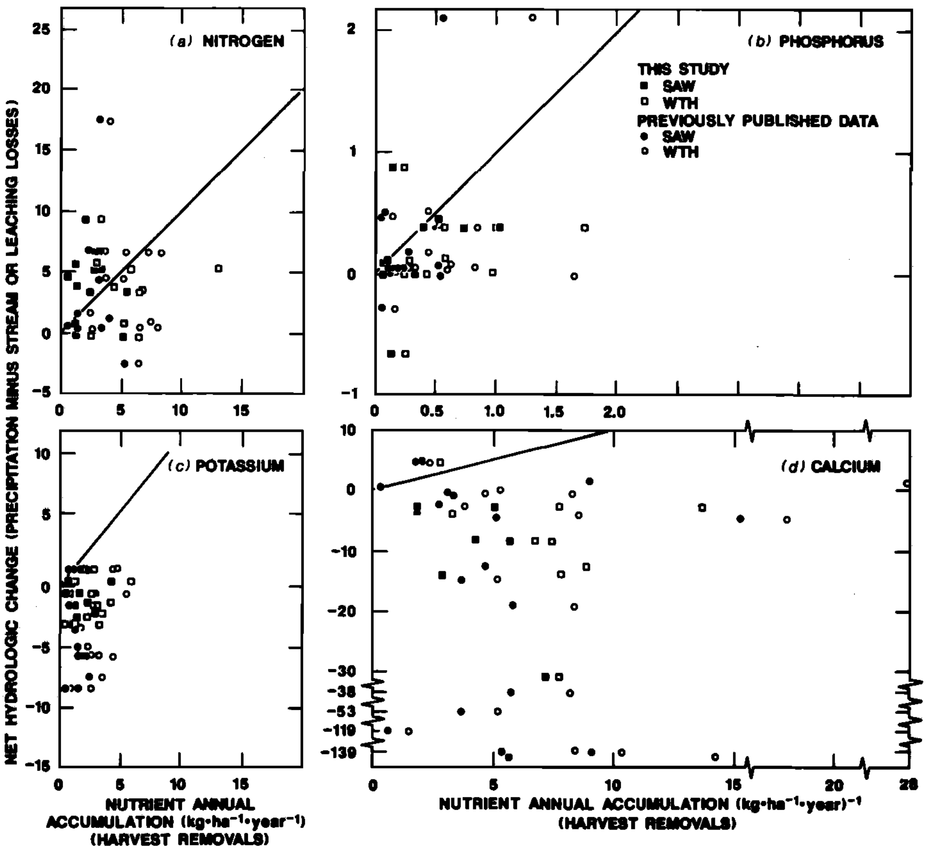

FIGURE 3. Net fluxes (bulk deposition minus leaching and/or runoff) of nutrients in relation to estimated removals of nutrients in harvested wood. Lines indicate net hydrologic change equal to harvest removals. Each stand is represented by open symbols that indicate total above-stump biomass (assumed to be equivalent to WTH) and closed symbols that indicate total stem biomass (assumed to be equivalent to SAW). Not all previously published data included stem biomass estimates. Points above the line indicate net hydrologic gain of nutrients; points below the line indicate net hydrologic losses of nutrients.

fixation in frequently burned Coastal Plain forests resulted in higher N content in soils than in soils of unburned sites.

Net changes in the other macronutrients were very different from net changes in N, especially with WTH. Approximately 70% of all stands showed a net loss of P (Figure 3b) with SAW and an 80% loss with WTH. Net losses of K and Ca (Figure 3c and d) occurred in nearly all sites. Net Ca losses generally fell in one of two groups: those more than 50 $kg \cdot ha^{-1} \cdot yr^{-1}$ and less than 20 $kg \cdot ha^{-1} \cdot yr^{-1}$. All of the sites that lost large quantities of Ca were on limestone-derived soils or were high in Ca content.

While there were no known Ca deficiencies in any of the stands discussed here, the nutrient that showed the greatest loss in most cases was Ca. This suggests that Ca was not conserved very effectively in these ecosystems and will probably be the nutrient showing greatest declines with intensive management. The implications of such declines in Ca, should they occur, are unknown.

Lindberg et al. (1986) recently estimated the relative contribution of dry deposition of macronutrients. By combining their estimates of dry- to wet-deposition ratios with the National Atmospheric Deposition Program estimates of wet deposition (NADP 1985), we made a preliminary estimate of nutrient additions in dry deposition. From those data, we estimated an additional 3 to 8 $kg \cdot ha^{-1} \cdot yr^{-1}$ of N, 0.5 to 1.0 $kg \cdot ha^{-1} \cdot yr^{-1}$ K, and 3 to 5 $kg \cdot ha^{-1} \cdot yr^{-1}$ Ca from dry deposition in most of the eastern United States. These amounts would result in net gains in N at most sites considered in this paper, without N-fixation. An additional 3 to 5 $kg \cdot ha^{-1} \cdot yr^{-1}$ of Ca would result in net gains at some sites, especially those with conventional harvest. Potassium and phosphorus have larger losses than gains, even without harvests at most sites, but total K in most soils is very high (Freedman 1981) and contributions from weathering are unknown.

Regrowth

The first year after harvest, regrowth biomass was less with SAW than with WTH at two of three sites with both harvest treatments (Table 6). After 5 years, regrowth biomass at the Clemson site was almost 30% higher with SAW than with WTH. Growth trends at the Clemson site cannot be attributed directly to effects of harvest method on soil fertility. At Clemson, herbaceous biomass during the first 2 years was 25 to 50% greater with WTH. Intense herbaceous competition may have contributed to lower total (predominantly pine) biomass on this watershed after 5 years. Nutrients (except Ca) in the regrowth equaled or exceeded those in the preharvest biomass at the Clemson site (Cox and Van Lear 1985). After 4 years, total standing biomass increased with SAW to more than 1.5 times that with WTH at the Oak Ridge site (Mann, unpublished data). Regrowth at the Coweeta site was similar after both treatments.

DISCUSSION AND CONCLUSIONS

The major effects of WTH compared with those of SAW lie in removals of nutrients and organic matter in harvested material rather than in changes in nutrient export via leaching and runoff. When compared with SAW, WTH resulted in disproportionately greater nutrient removals than biomass re-

TABLE 6. Biomass in kg/ha of regeneration after harvest.

Site	Years since harvest	WTH	SAW
Oak Ridge[a]	1	1765	1837
	2	3215	4115
	3	4499	6971
	4	8873	12854
Coweeta	1	2339	1725[b]
	3	8106	6912
Clemson[c]	1	3130	2456
	2	5800	3510
	5	16065	20775
Cockaponset[d]	1	1540	
	3	7830	

[a] Man 1984 and unpublished data. Biomass does not include foliage.
[b] Boring et al. 1981.
[c] Cox and Van Lear 1985.
[d] Martin et al. 1987.

moval in both hardwood and conifer stands because of higher nutrient concentrations in twigs and branches than in stems. Underutilization of stems in hardwood stands with SAW also contributed to the much larger removal of nutrients in hardwood stands with WTH.

The large difference in amounts of nutrients left on-site by SAW compared with those left by WTH did not cause major differences in leaching or runoff losses at sites where comparisons were made. Except for slight increases in P losses in the first few years after harvest, WTH did not result in greater hydrologic losses of nutrients than did SAW. Differences in hydrologic losses of P and N that were significant were small relative to differences in nutrient removals in wood harvested with WTH and SAW. Regrowth may have been a major nutrient conservation mechanism (Marks and Bormann 1972, Boring et al. 1981, Cox and Van Lear 1985). On sites where residues strongly affect the rate of establishment of vegetation after harvest, hydrologic losses of nutrients may be affected.

The frequency of occurrence of increased NO_3^- in soil solution and stream water after harvest suggests that both SAW and WTH contribute to increased nitrate losses by enhancing nitrification rates. An exception to this generalization occurred in the red alder stands where harvesting actually reduced NO_3^- losses, presumably because N-fixation was terminated with the removal of the tree cover. The frequent decreases in NH_4^+ leaching losses following harvests indicates that nitrifying organisms were more active after harvest, that there was more NH_4^+ uptake, or that less organic-N substrate was available for mineralization. Although SAW and WTH resulted in increased retention of nutrients compared to uncut stands at some sites and increased losses at others, net changes for both treatments were minor compared to the magnitude of harvest removals, with the possible exceptions of K and Ca at some sites.

Our comparisons of net hydrologic changes and estimated harvest removals predict that, except for N, harvested systems lose nutrients regardless of harvest intensity. Even though N is undoubtedly limiting on many sites in the sense that added N fertilizer would result in greater growth, P appears to be the nutrient most likely to be reduced from most sites by both SAW and WTH if not replenished by weathering. Because hydrologic losses of P apparently were slightly greater immediately after WTH than after SAW, P losses may be exacerbated by WTH. Our studies also indicate Ca is likely to be reduced in hardwood sites in the eastern United States. On limestone-derived soils, deep rooting or higher rates of mineral weathering may replenish Ca supplies (Johnson et al. 1982), but at other sites, Ca losses may be a problem.

Although the evidence of early growth responses suggests that WTH can reduce growth on some sites (Cox and Van Lear 1985, Mann, unpublished data), causes of this reduction are difficult to isolate. Surface soil textural differences and intense herbaceous competition with WTH may have adversely affected pine growth at Clemson (Cox and Van Lear 1985). The influence of initial differences in site disturbance, subsequent effects of herbaceous competition or the influence of residues on microclimate and nutrient release from decomposing woody residues (Barber and Van Lear 1984) on regrowth remain unknown. Hence, the occurrence or magnitude of growth reduction cannot yet be predicted from nutrient budget analyses. Longer term studies in SAW and WTH regenerating ecosystems are needed to establish production trends and reasons for differences in regrowth patterns. Studies at some of the sites are pursuing these needs.

Difficulties with using budget analyses to predict the effects of whole-tree harvest on subsequent productivity have been discussed at length (Boyle et al. 1973, Leaf 1979, Clayton 1979, Alban 1979, Freedman 1981, Smith et al. 1986). These difficulties include the unknown relationship of site fertility, as indicated by nutrient budgets, to growth of different species and the largely unknown rates of mineral weathering and atmospheric nutrient contributions.

Although this study also deals with nutrient budgets and is subject to the same limitations, we have demonstrated that (1) the magnitude of nutrient removal across a broad spectrum of commercial forests can be predicted, (2) most forest systems are losing nutrients at a much greater rate via harvest relative to hydrologic inputs, and (3) WTH causes relatively little effect on hydrologic nutrient losses compared to SAW.

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